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BUILDING POUNDING RE-EXAMINED: HOW SERIOUS A PROBLEM IS IT ?

S. A. ANAGNOSTOPOULOS

Department of Civil Engineering, University of Patras
26500 Patras, Greece

ABSTRACT

A detailed review of the published references to pounding damage in past earthquakes is presented, followed by a brief review of analytical and numerical investigations of this problem by several investigators. The limitations of the mathematical models used are pointed out and the results are discussed in relation to these limitations and to the available field evidence. It is concluded that for the vast majority of neighbouring buildings with similar heights and structural characteristics, the effects of pounding will be limited to some local damage, mostly non-structural or light structural, and to higher in-building accelerations in the form of short duration spikes. Only when the colliding buildings have much different masses, periods and heights, can pounding be a serious problem and a threat to safety. Most of the observed failures or collapses that have been attributed to pounding have occurred when the top of a shorter building hammered at a midstory of its taller neighbour, shearing its columns. Use of special "bumper" shear walls is suggested as a good alternative to the seismic separation requirement, especially for situations where a new building is to be built next to existing structures with zero seismic separation.

KEYWORDS

Pounding; building response; earthquake damage; impact; collisions; adjacent buildings; seismic separation; seismic joint.

INTRODUCTION

Large earthquakes in the past 15 years have brought to the attention of earthquake engineers and researchers the problem of collisions between insufficiently separated neighbouring buildings. Field evidence has indicated that this problem, also known as pounding, has caused damage ranging from light to heavy, while in certain cases it might have even initiated failures. Pounding may be expected in city blocks, where buildings are in contact to each other, in cases of buildings with external stairway towers or between units of interconnected complex structures such as hospitals, schools or industrial facilities.

Work on this subject intensified in the past 10 years, especially after the 1985 earthquake that struck Mexico City causing an unusually large number of building failures, in some of which pounding appeared to have played a primary role (Rosenblueth and Meli, 1986). In this respect, the Mexico City damage is unique, because in no other earthquake has pounding been determined as a leading cause of building collapse, except in very few and rare cases.

To avoid this problem, modern codes require a seismic separation between adjacent buildings. Of course, this cannot affect the great numbers of buildings constructed before such requirements were introduced. Moreover, even for new construction the seismic separation requirement may not be easy to apply, as there is strong opposition by property owners, developers and engineers for a number of economic, technical and legal reasons (Anagnostopoulos, 1988). In addition, two other arguments are often heard against the seismic separation requirement. The first is drawn from field observations in past earthquakes, which indicate that although great numbers of buildings have been subject to pounding, only a tiny fraction suffers damage from it, while the fraction with serious damage and perhaps failure as a result of pounding alone is often negligible. The second argument, drawn both from field observations and numerical studies, is that weak buildings in contact with stronger buildings in a city block may actually benefit from such contact, provided that pounding will not cause any serious local damage from which failure could be initiated. The above suggest a need for re examination of this problem by reviewing the available evidence of pounding damage in past earthquakes, by reassessing results from numerical investigations and, further, by looking for alternative **practical solutions** that could minimise or even eliminate the seismic separation requirement.

RECORDED EVIDENCE OF POUNDING

Since the field evidence from past earthquakes is the best yardstick to assess the importance of most earthquake engineering problems, a detailed and careful review of the available observations and assessments of pounding damage (or no - damage) is a prerequisite for proper interpretation of analytical or numerical results and even more so for the recommendation of preventive or protective measures. Such a review has been presented by Anagnostopoulos (1995), based on reconnaissance reports from the following earthquakes:
1. The Great Alaska earthquake (1964)   2. The Tokachi-Oki earthquake, Japan (1968)   3. The Managua earthquake (1972)   4. The Guatemala earthquake (1976)   5. The Friuli, Italy, earthquakes (1976)   6. The Romania earthquake (1977)   7. The Greek earthquakes of Thessaloniki (1978), Alkyonides (1981) and Kalamata (1986)   8. The Mexico earthquake (1985)   9. The Loma Prieta earthquake (1989).

While this survey is by no means complete, a serious effort had been made to locate and include the most well known cases of heavy damage or structural failures, for which pounding was considered as a primary cause. There is at least an equal number of events, not included in the above list, for which no reference to pounding could be found in the pertinent reconnaissance reports. After the aforementioned review was made, two new strong earthquakes have hit metropolitan areas: The Northridge, 1994, and the Kobe, 1995, earthquakes. The information for these two earthquakes may not be complete yet, but is still worth presenting.

10. The Northridge Earthquake (1994)

This earthquake, with a 6.4 Richter magnitude has affected a large populated area near Los Angeles. The only source of information available to the author when this paper was written is an EERI preliminary reconnaissance report (Hall, 1994), in which there are only three references to pounding damage: one in relation to canopies and covered walkways in public schools, a second on the collapse of a tilt-up wall, to which the hammering by some storage racks may have contributed, and a third pertaining to hospital buildings, for which, "seismic separation joints worked as anticipated causing minor cosmetic damage to facilities". Although the exact number or even a rough estimate of all the buildings subject to pounding in the affected area is not available, it is estimated to be large. Then on the basis of the cited EERI report, which admittedly may not provide an adequate survey of the effects of pounding, it would appear that pounding was not an important factor contributing to building failures or to heavy structural damage in this event.

11. The Hyogo-Ken Nanbu (or Kobe) Earthquake (1995)

This major and devastating earthquake, with a moment magnitude of $M_w = 6.9$, hit the Japanese city of Kobe killing over 5.000 people, injuring over 26.000 and leaving over 300.000 people homeless. In view of the vast number of collapsed buildings, the great extent of damage and the limited, as yet, amount of published information in the form of damage surveys, it will be premature to draw any conclusions on the importance of pounding from this earthquake. We will only mention the following two references to pounding in an EERI preliminary reconnaissance report (Comartin et al, 1995): "Smaller buildings are typically built immediately adjacent to each other and interaction (pounding) would often "push" the end or corner building out into the street" and another one, "In some cases the collapsed story could be associated with structural irregularity, such as a set back or interaction with an adjacent structure".

From the above 11 events, for which pounding has been reported, the Mexico, 1985, earthquake appears to be unique in terms of pounding damage. However, the original assessment by Rosenblueth and Meli (1986) that is often cited, i.e." In over 40% of collapsed or seriously damaged buildings, there was pounding with adjacent structures. Sometimes pounding caused minor local damage. In 15% of all cases it led to collapse", may haven been an overstatement creating wrong impressions. In a personal communication with the second author, the following clarifications were given (Meli, 1994): "In 15% of building with major damage or collapse (not only collapse) evidence of pounding was found. Not necessarily pounding was the main cause of collapse. Probably only in 20-30% of these cases pounding could have been a significant factor in the structural damage". This is obviously a much weaker statement on the effects of pounding, compared to the earlier assessment. Moreover, it appears that pounding did not cause any major damage when floor levels coincided (Meli, 1994) and, further, that most of the damage occurred in the centre of Mexico City, where there is a concentration of engineered buildings practically in contact to each other and having different height, different structural systems or different configurations (Bertero,1986). Although in comparison to other earthquakes the above numbers appear large, they are quite small compared to the total number of affected buildings. Moreover, it is still open to question whether pounding alone would have led to collapse in most of the cases it did, if other deficiencies (e.g. in design, construction etc.) were not present.

The above suggest that although pounding is frequently observed in strong earthquakes, it has little effect on the great majority of buildings that have or could have been subjected to it. In most of the cases where it occurs, it usually causes local damage, non-structural or minor structural. The few incidents of major damage or even failures due to pounding are seen almost always when the columns of a building are hammered at mid-story by the top of a shorter, stiff and massive structure.

RESULTS FROM NUMERICAL AND ANALYTICAL STUDIES

Results from numerical investigations of earthquake induced pounding are quite useful for assessing the importance of the main pertinent parameters. In view, however, of the complexity of the real problem and the many variations under which it may be encountered, generalisations of conclusions from numerical studies and extrapolations to actual practice should be made with caution and, if possible, only if corroborated by field observations. This has not been always the case in the past, as the enthusiasm from some nice numerical or analytical solutions tends to make people forget the limitations and simplifications under which such solutions have been obtained. Due to space limitations, only some representative results will be presented here. A more detailed review may be found elsewhere (Anagnostopoulos, 1995).

Most of the numerical and all of the analytical work on pounding has been based either on pairs of colliding SDOF oscillators or on a single oscillator colliding at one or both sides with a rigid, fixed or moving, barrier (e.g. Wolf and Skrikerud, 1980, Miller, 1980, Jing and Young, 1990, Davis, 1992). Numerical studies have also been carried out with series of several systems simulating building rows in a city block (Anagnostopoulos, 1988, Athanassiadou et al, 1994). In all pertinent work, the collisions between adjacent buildings are simulated either by means of special contact elements (of the spring - dashpot type) or by applying the impact laws of mechanics for particles, with a coefficient of restitution for plastic impacts. The first approach can provide a better approximation to the real problem, under the condition that appropriate values of the impact element properties are used. And while these properties are highly uncertain and hence difficult to determine with accuracy, it turns out that the response is quite insensitive to wide changes in their values (Anagnostopoulos 1988). The stiffness of the impact spring is typically large and represents the local structural stiffness at the point of impact that will react to the shock during contact. The constant of the associated dashpot determines the amount of energy dissipated during impact and its value can be estimated in terms of the coefficient of restitution by the following relationship (Anagnostopoulos 1988).

$$\left.\begin{aligned} c &= 2\xi_i\sqrt{K\cdot\frac{m_1 m_2}{m_1+m_2}} \\ \xi_i &= \frac{-\ln\varepsilon}{\sqrt{\pi^2+(\ln\varepsilon)^2}} \end{aligned}\right\}$$

where: c = damping constant, ε = coefficient of restitution, lnε = natural logarithm of ε, K = stiffness of the impact spring, m_1, m_2 = colliding masses, and ξ_i = damping ratio.

Solutions with the SDOF oscillator pounding on the rigid boundary indicate a frequency shift of the impacting system towards high frequencies that is usually accompanied by a deamplification of peak response and, for certain parameter combinations, by an amplification of such response. While such results provide a good insight on the mechanics of the simple systems examined, they cannot be easily extrapolated to actual conditions due to the many oversimplifications involved (SDOF systems, collisions against a barrier, elastic response of structure, highly idealized input motion, etc.). If one ignores the adverse local effects of pounding, then the cited studies indicate that the global response is usually reduced as a result of the collisions, which act in effect as a damping mechanism. On the other hand, Wada et al (1984) have shown that for inverted pendulum type structures, for which P-δ effects are important, pounding may initiate collapse.

In the case of several adjacent buildings, detailed investigations of elastic and inelastic SDOF systems has shown, through a wide variation of all key parameters, that for systems with similar characteristics pounding may amplify or deamplify their response and, further, as the difference in period and mass of the colliding systems increase, so do the effects of pounding (Anagnostopoulos, 1988). Moreover, it was found that pounding effects may be more pronounced for end than interior systems. A study by Athanasiadou et al (1994) has confirmed these results and further suggested, on the basis of a rough approximation, that travelling wave effects may be important only for long rows of buildings.

As the interest on pounding increased in recent years, more refined models based on MDOF, lumped mass systems were analyzed with a variety of solution methods. As with SDOF systems, the collisions are again simulated either by means of contact elements (spring-dashpots) or by using the coefficient of restitution approach. Many of these studies have focused primarily on solution techniques of the resulting mathematical problem for two adjacent systems (see e.g. Anagnostopoulos, 1995, for a rather detailed review), while others have aimed at a better understanding of the real problem by means of parametric investigations using more than one earthquake motions (Anagnostopoulos and Spiliopoulos, 1992, Spiliopoulos and Anagnostopoulos, 1992, Maison and Kasai, 1992). The results by Maison and Kasai, 1992, are for two elastic buildings pounding against each-other at a single, pre-selected point. These limitations are imposed by the modal method of solution used (the method becomes extremely cumbersome to apply for more than one points of contact), rendering the results applicable only to pairs of buildings pounding at a single point in the elastic range. A wider set of practical problems has been addressed by Anagnostopoulos and Spiliopoulos, 1992, who have idealised series of buildings as lumped mass, MDOF systems with bilinear force-deformation characteristics and with viscoelastic supports (Fig. 1). Collisions between adjacent masses could occur at any floor level and were simulated by means of viscoelastic impact elements. The main limitation of this work is that the MDOF systems were taken as shear beam type, with one stiffness element per story, and thus the results are only applicable to pure frame - type buildings. A further consequence of this is that midstory collisions cannot be studied in any meaningful way and so the usual restriction of collisions at the floor levels has also been applied. Using five real earthquake motions, extensive parametric studies were performed to assess the importance of the following factors: building configuration and relative size, seismic separation distance and impact element properties. Typical results from Anagnostopoulos and Spiliopoulos (1992) are shown in Fig. 2 for rows of 3 adjacent buildings with 5 stories (1st & 2nd set of graphs) and with 10 stories

(3rd & 4th set). Results are given for one and two - sided pounding, i.e. for end and interior buildings in the row, as indicated at the top of each graph. In the case of the 5 - story group, the system with period T=0.36 s is examined and in the case of the 10 - story group the system with T = 1.03 sec is examined. The three lines in each graph correspond to the three configurations shown at the top of the figure. The abscissas are mean values of the ratios V/V_o (upper graphs - elastic response) and μ/μ_o (lower graphs - inelastic response) for the five real earthquake motions, where V and μ are maximum story shear and ductility factor, respectively, when the buildings are in practical contact, and V_o, μ_o are the same quantities without pounding. What one may conclude from the graphs of Fig. 2 is that under conditions similar to those for which these graphs have been obtained, i.e. for buildings of same height with consistent design strengths, similar masses and same floor elevations (collisions occurring only at floor levels), the effects of pounding on global response are insignificant in most cases. Moreover, these results do not indicate that end buildings are penalized by

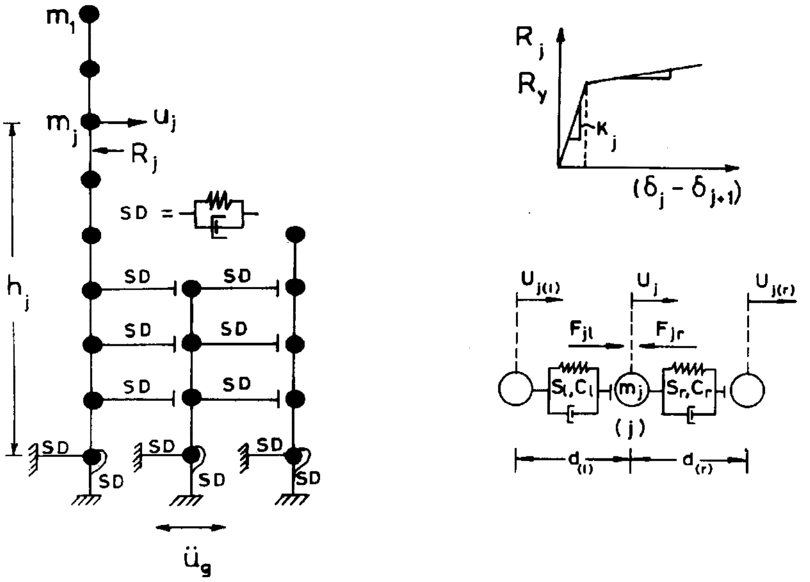

Fig. 1: Idealization of adjacent buildings.

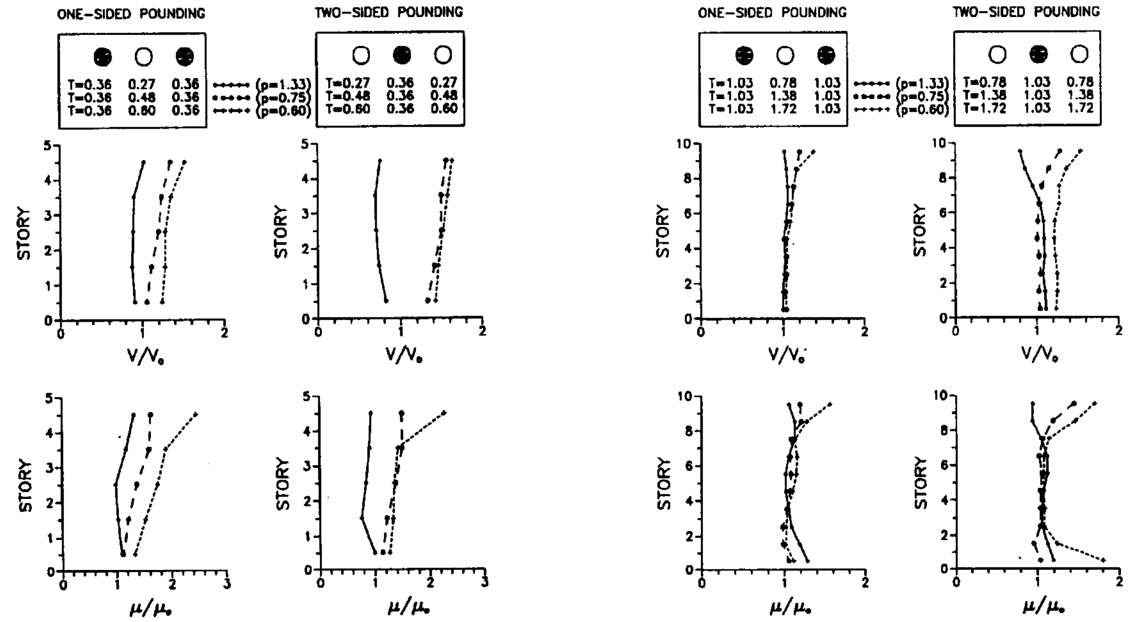

Fig. 2: Effects of pounding on elastic and inelastic response of 5 and 10-storey systems
(T = period, system examined shown shaded)

pounding more than interior buildings. Only when there is a great difference between the periods of the two colliding buildings and only if the stiffer of the two structures gets into the inelastic range, ductility amplifications on the order of 2 may be considered as indicative of significant response increase due to pounding that may be associated with some structural damage. Under normal conditions and if other weaknesses are not present, such amplifications may be deemed tolerable. Taking also into account that under conditions of similar height and construction, adjacent buildings will have periods that are probably quite close, the results of Fig. 2 suggest negligible effects of pounding on overall response. This is in full agreement with the field evidence from past earthquakes discussed earlier.

The consequences of pounding can be far more serious if the colliding buildings have different heights, as indicated in Fig. 3 from Anagnostopoulos and Spiliopoulos (1992). Here, in addition to the mean ductility amplification ratios, the maximum values from the five motions are also plotted for two cases of stiffness of the shorter building. In situations like these the effects of pounding can be severe. They may even become catastrophic if the top slab of a stiff and massive lower building strikes the taller building not at a floor level but at column midheight. In the latter case, the impact can severely damage columns of the tall building initiating failure or even collapse. In the author's opinion, this constitutes by far the most dangerous situation of pounding, amply documented from failures in past earthquakes. It is for such cases that specific protective measures to prevent pounding or alleviate its effects are quite necessary.

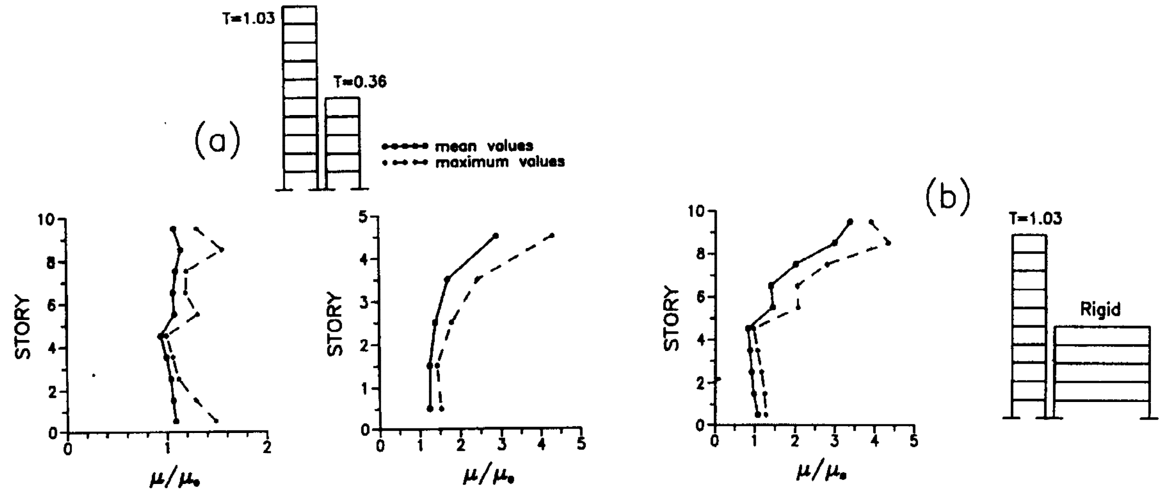

Fig. 3: Effects of pounding on the inelastic response of buildings with unequal heights.

MEASURES AGAINST POUNDING

The typical measure against pounding, one that modern codes specify, is to provide a sufficient separation distance between the neighbouring buildings. Thus, the UBC code specifies a minimum separation for each building of $3R_w/8$ times the displacement due to the design seismic forces (R_w = response modification factor). A similar provision will be found in EC-8, the European pre-standard for earthquake resistant design, except that the separation is reduced to 0.7 of its value if the floor elevations of the two adjacent buildings coincide. In addition, EC-8 relaxes the separation requirement, as does the Greek code, if a building has at least two collision shear walls at its two ends perpendicular to the property line and extending over the total height of the building. In such cases, the separation distance for the rest of the building can be reduced to 4.0 cm.

The code specified separations, equal to the absolute sums of the design maximum displacements of the two buildings, were found to be quite adequate for protection against pounding and so did the reduced values determined as the SRSS of the same displacements (Anagnostopoulos and Spiliopoulos, 1992, Maison and Kasai, 1992). A more refined estimate of the required separation, based on random vibrations has been proposed by Jeng et al (1992) and appears to give excellent results, at least for elastic systems .

As an alternative to seismic separation, permanent connections of the adjacent buildings have been investigated by Westermo (1989). While this method could, in principle, be used to eliminate pounding, it may be quite expensive and difficult to apply, if provisions for it had not been made when each building was constructed. Moreover, such connections seem to increase the response of the stiffer building while reducing the response of the more flexible one, a consequence that would not be acceptable by the owner of the penalized stiffer building. Another measure for reducing the effects of pounding, while maintaining small separation distances, would be to fill the gap with a special, shock absorbing material (Anagnostopoulos, 1988). This approach needs further investigation to evaluate its technical and economic feasibility.

In view of the above, it appears that the best alternative to the seismic separation might be to provide strong shear walls to act as "bumper" elements protecting the rest of the building (Anagnostopoulos and Spiliopoulos, 1992). This alternative, shown in Fig. 4, has already been incorporated in the new Greek code and in EC-8 for earthquake resistant design. It is also quite attractive because it solves the thorny problem of new construction next to older buildings already built up to the property line (zero seismic separation), by protecting the new building while precluding mid-story column hammering of the existing buildings.

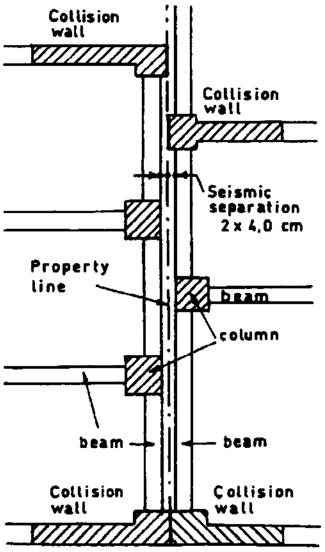

Fig. 4: Horizontal section of two adjacent building frames with collision walls

CONCLUSIONS

On the basis of the available evidence from past earthquakes and of the results from numerical and theoretical studies presented or cited herein, the following conclusions pertaining to earthquake induced pounding between adjacent buildings may be summarized:

1. Earthquake induced pounding can have adverse or beneficial effects on the overall displacement response of a building in a block, depending primarily upon its period and mass in relation to the period and mass of the building(s) next to it. As a rule, when the masses of the two buildings are similar, the response of the stiffer building will be amplified and of the softer building deamplified. From a practical point of view, the amplifications will be insignificant, if the buildings have similar heights. The position of the building in the row - i.e. end or middle - appears to have a lesser influence compared to the other parameters.
2. Pounding will always cause local damage at the points of impact, which under certain circumstances (see next conclusion) may initiate failures. Moreover, pounding will induce higher accelerations in the form of short duration spikes that will increase the anchoring requirements for the contents of the building.
3. High displacement amplifications due to pounding result only if the colliding buildings are significantly different in height, period and mass. Differences in height in particular can create serious problems, especially if the shorter of the two buildings is massive and stiff. Most of the observed failures or

collapses that have been attributed to pounding have occurred when the top of a shorter building hammered at a midstory of its neighbour, shearing its columns.

4. It appears that the SRSS of the code specified peak design displacements is sufficient to avoid pounding or to minimize its effects.
5. The number of buildings that have suffered structural damage due to pounding in past earthquakes is a minute percentage of all the buildings that are in contact to each other and subjected to these earthquakes. Even smaller is the percentage of buildings in which pounding has been considered as the initiating cause of collapse. This is a strong argument used by people who are against the code requirement of seismic separation and it makes sense in the case of building blocks in which the adverse conditions described under (3) above are not present. In any case, a good compromising solution will be to provide "bumper" or collision shear walls at the boundary lines and keep the rest of the building protected with a minimum of seismic separation, as shown in Fig. 4 and as the new Greek code and the European pre-norm EC-8 permit.

REFERENCES

Anagnostopoulos, S.A. (1988). Pounding of buildings in series during earthquakes, *Earthq. eng. struct. dyn.*, **16**, 443-456.

Anagnostopoulos, S.A. and Spiliopoulos K.V. (1992). An investigation of earthquake induced pounding between adjacent buildings. *Earthq. eng. struct. dyn.*, **21**, 289-302.

Anagnostopoulos, S.A. (1995). Earthquake induced pounding: State of the art. In: Proc., 10th European conf. earthquake eng. (Duma Ed.), Balkema, Rotterdam, 897-905.

Athanassiadou, C.J., Penelis, G.G. and Kappos, A.J. (1994). Seismic response of adjacent buildings with similar or different dynamic characteristics, *Earthq. spectra*, **10**, 293-317.

Bertero, V.V. (1986). Observations on structural pounding. Proc. Intrnl. Conf. Mexico earthquakes, ASCE, 264-287.

Comartin, C.D., Greene, M. and Tubbesing, S.K. (Eds), (1995). The Hyogo-Ken Nanbu Earthquake Jan. 17, 1995. Earthquake Engineering Research Institute, Preliminary Reconnaissance Report, EERI-95-04.

Davis, R.D. (1992). Pounding of buildings modelled by an impact oscillator. *Earthq. eng. struct. dyn.*, **21**, 253-274.

Hall, F.J. (Ed.), (1994). Northridge Earthquake, Jan. 17, 1994. Earthquake Engineering Research Institute, Preliminary Reconnaissance Report, EERI-94-01.

Jeng, V., Kasai K. and Maison, B. (1992). A spectral difference method to estimate building separations to avoid pounding. *Earthq. spectra*, **8**, 201-223.

Jing, H.S. and Young, M. (1990). Random response of a single-degree-of-freedom vibro-impact system with clearance. *Earthq. eng. struct. dyn.* **19**, 789-798.

Maison, B.F. and Kasai, K. (1992). Dynamics of pounding when two buildings collide. *Earthq. eng. struct. dyn.*, **21**, 771-786.

Meli, R. (1994). Personal Communication.

Miller, R.K. (1980). Steady vibroimpact at a seismic joint between adjacent structures. Proc. 7th world conf. earthquake eng., Istanbul, **6**, 57-64.

Rosenblueth, E.and Meli R. (1986). The 1985 earthquake: causes and effects in Mexico City. *Concrete Intnl. ACI*, **8**, 23-36.

Spiliopoulos, K.V. and Anagnostopoulos, S.A. (1992). Earthquake induced pounding in adjacent buildings. Proc. 10th world conf. earthquake eng., Madrid. Balkema, Rotterdam, 2887-2892.

Wada, A., Shinozaki, Y. and Nakamura, N. (1984). Collapse of building with expansion joints through collision caused by earthquake motion. Proc. 8th world conf. earthquake eng., San Francisco, **4**, 855-862.

Westermo, B.D. (1989). The dynamics of interstructural connection to prevent pounding. *Earthq. eng. struct. dyn.*, **18**, 687-699.

Wolf, J.P. and P.E. Skrikerud, (1980). Mutual pounding of adjacent structures during earthquakes, *Nucl. eng. des.* **57**, 253-275.